KEK Digital Accelerator
and
Latest Switching Device R&D

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on behalf of KEK Digital Accelerator Group

High Energy Accelerator Research Organization (KEK)
Tokyo Institute of Technology

19th International Symposium on Heavy Ion Inertial Fusion

12th August – 17th August 2012
in Berkeley

Contents

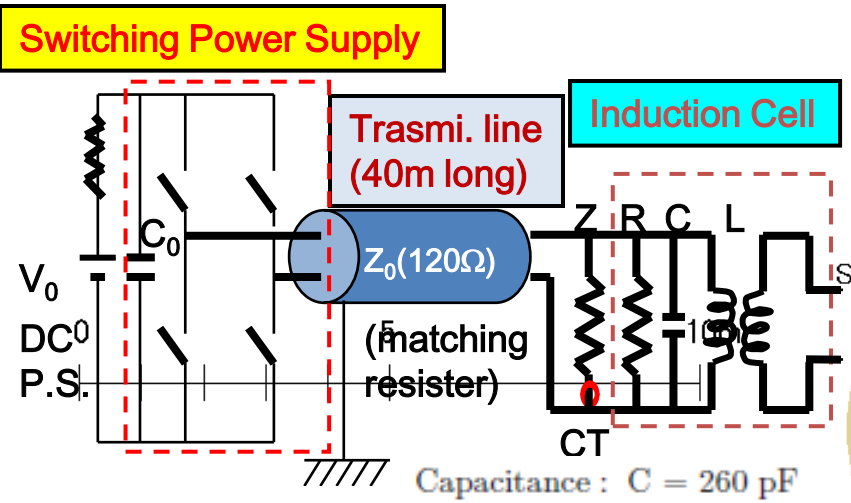
1. **Outline of KEK Digital Accelerator**
   (A fast cycle induction synchrotron *)
   - **Key components**
2. **Beam commissioning results**
3. **SPS development employing SiC-JFETs**
4. **Summary**

Companion paper (Poster Session of Thursday afternoon, 105):
T. Yoshimoto *et al.*, "Heavy Ion Beam Acceleration in the KEK Digital Accelerator: Induction Acceleration from 200 keV to a few tens MeV"

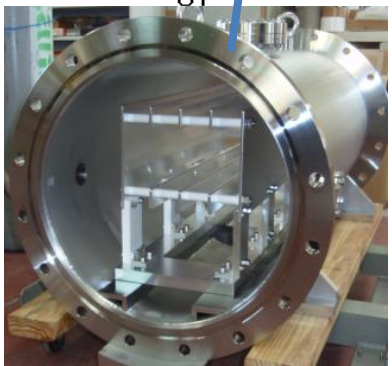
KEK Digital Accelerator (Rapid Cycle Induction Synchrotron)

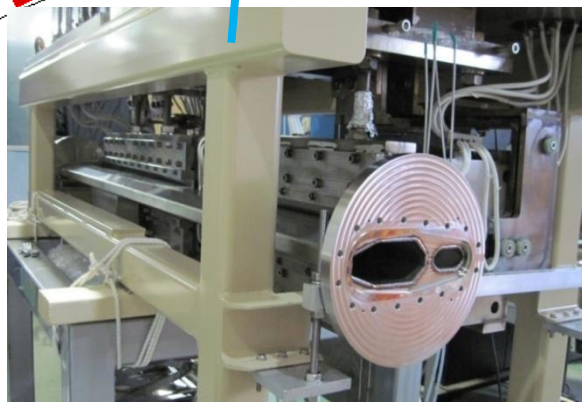
T. Iwashita *et al.*, *"KEK Digital Accelerator", Phys. Rev. ST-AB 14, 071301 (2011).*

Equivalent Circuit for Induction Acceleration System



ECRIS & 200 kV HVT





Einzel Lens Longitudinal Chopper : Idea, Device, Performance

Why we need a Chopper?

1 turn injection < 10 μsec

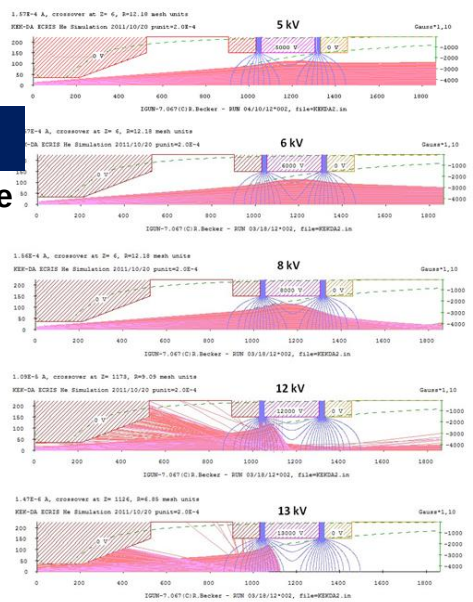
A long pulse from ECRIS ~ 2 - 5 msec

What type is desired?

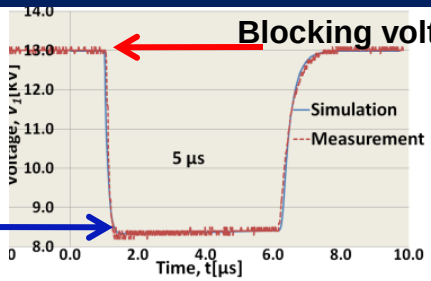
Low energy operation
Low cost (~ $2,500)

Low energy x-ray
Reduced out-gassing
Reduced secondary e⁻

Longitudinal gate study by IGUN

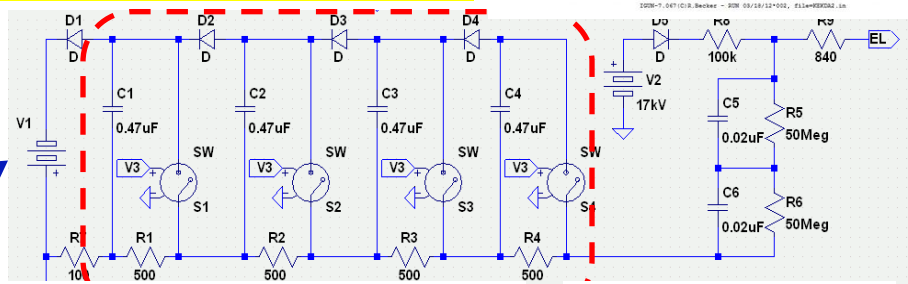


Voltage of middle electrode



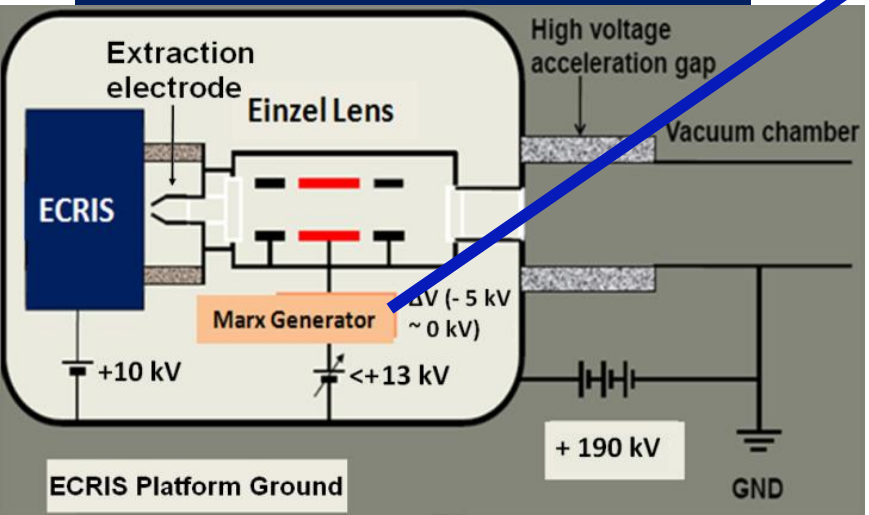
Optimized matching voltage

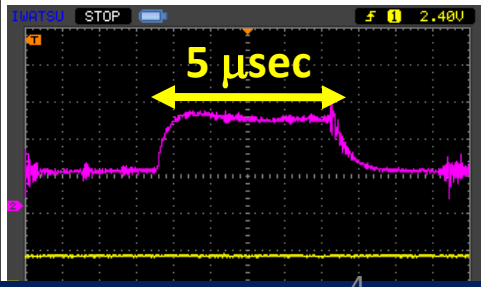
FET switch driven 4 stages Marx generator



Pulsed beam from ECRIS → Chopped beam

Einzel lens longitudinal chopper

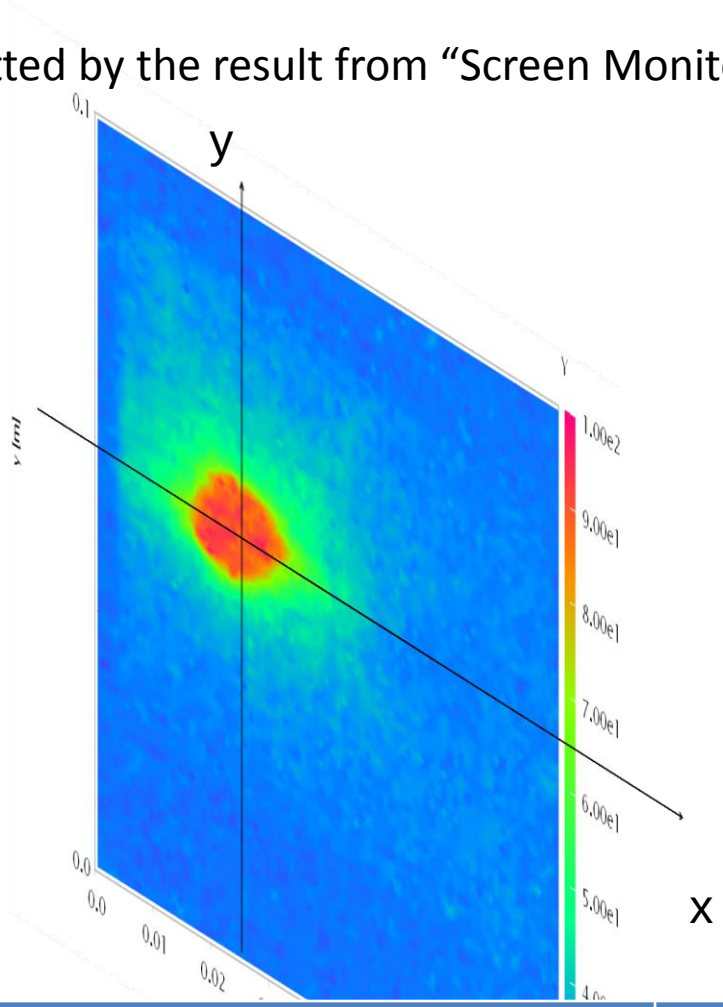




T.Adachi, K.W.Leo *et al.*, *Rev. Sci. Inst.* 82, 083305 (2011)

Beam Profile on the Screen Monitor placed upstream in LEBT

Beam profile plotted by the result from “Screen Monitor

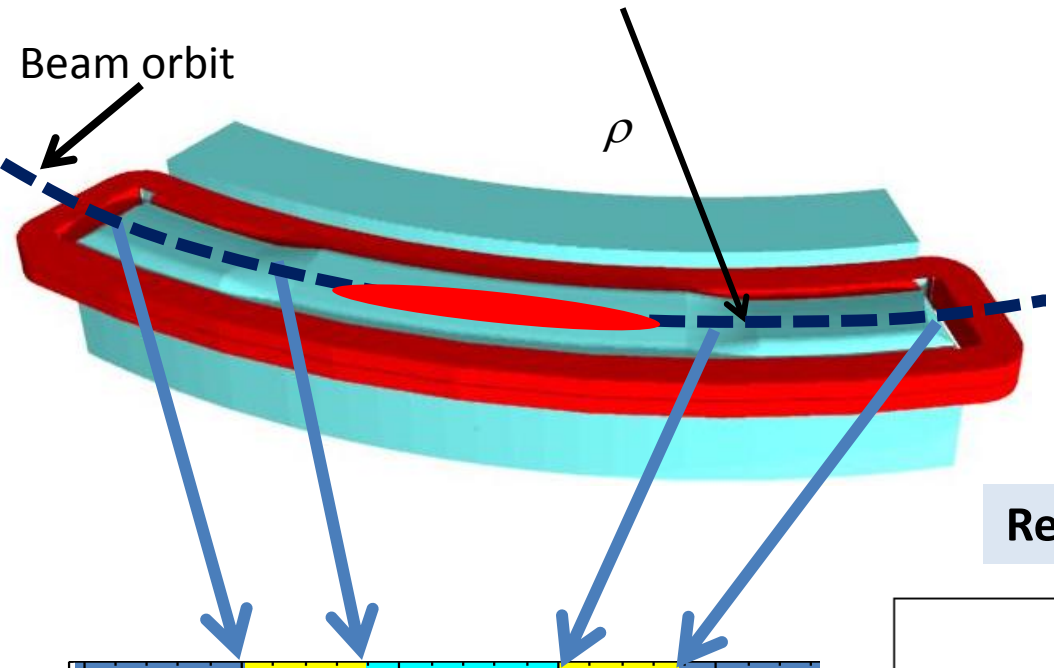


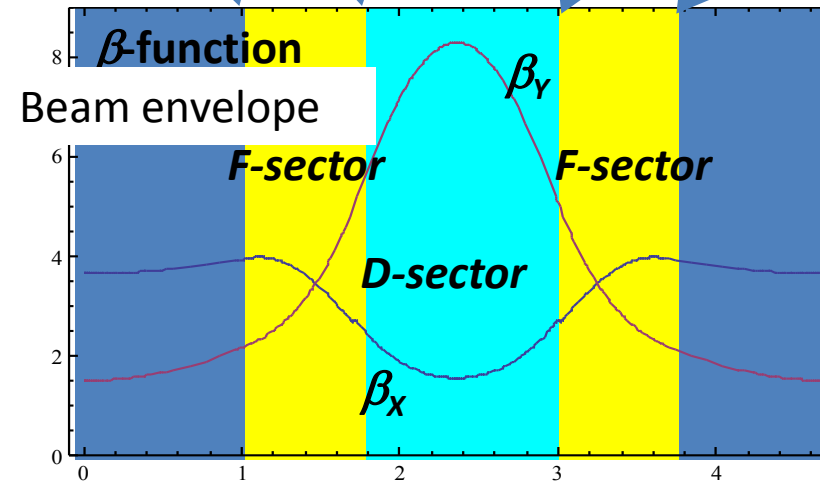
200 keV
H1+
100 μA

	Horizontal rms emittance ε_x[μmrad]	Vertical rms emittance, ε_y[μmrad]
Measuremenr by Pepper pot device	~100	~75

DA Ring Machine & Beam Parameters

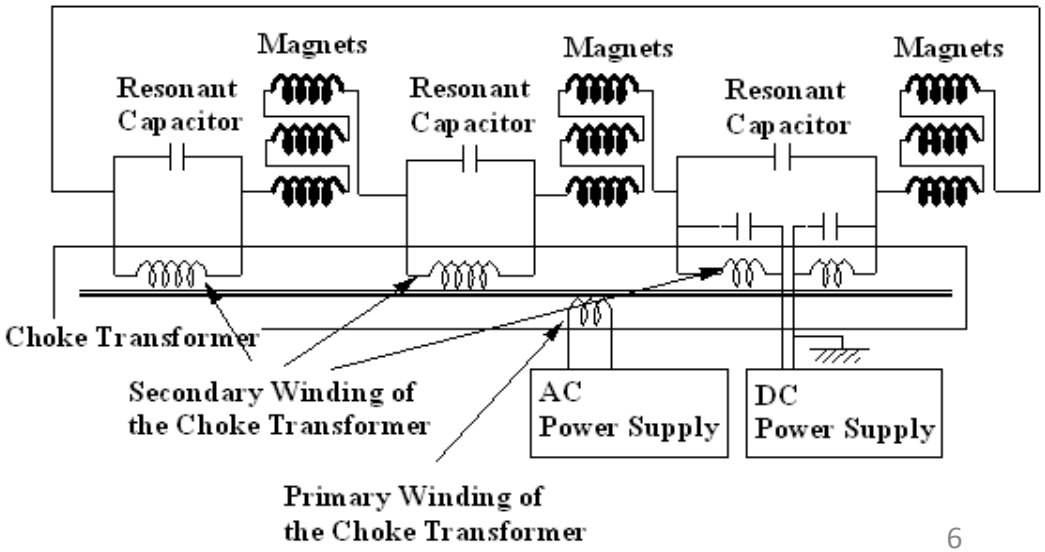
Combined-function type magnet (lower half)





Bending radius	ρ	3.3 m
Ring circumference	C_0	37.7 m
Maximum flux density	B_{max}	0.84 T
Accel. voltage/turn	V	3.24 kV
Repetition rate	f	10 Hz
Betatron tune	ν_x/ν_y	2.17/2.3

Resonant LCR Circuit Power Supply

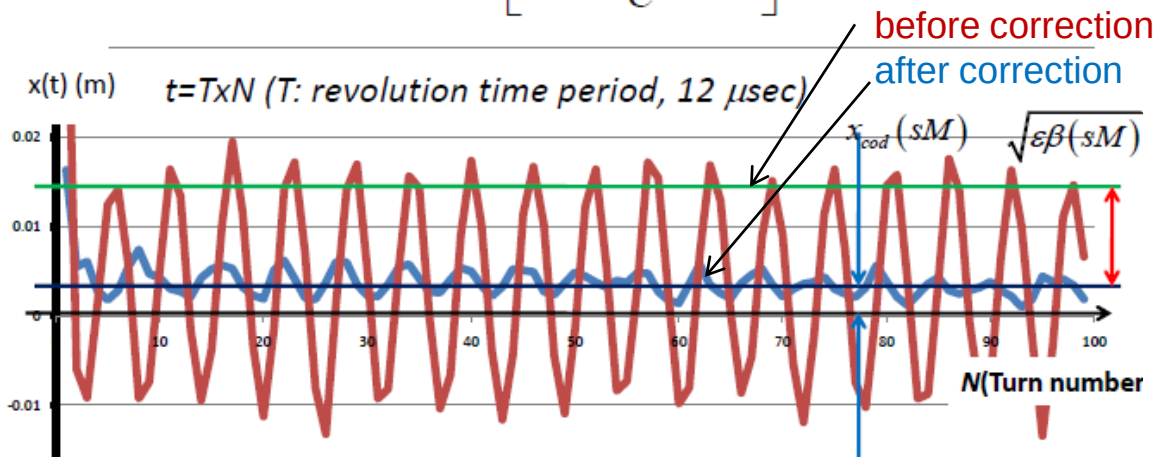


Beam Orbit Issues associated with Low Energy Injection

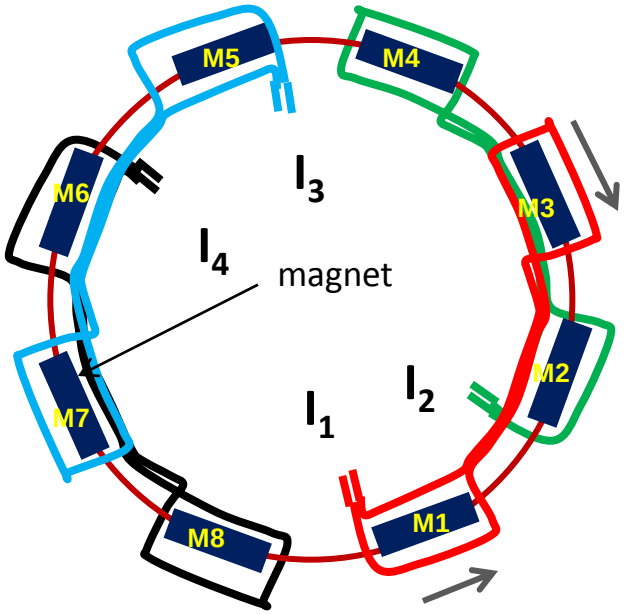
Injection Orbit Error

originated from error fields of upstream components

$$x(t) = \sqrt{\varepsilon\beta(sM)}\cos\left[2\pi Q\cdot\frac{v}{C}\cdot t+\delta\right]+x_{cod}(sM)$$



8 figure back-leg coil winding



Closed Orbit Distortion

originated from residual flux density in the main magnets

$$5\ \text{Gauss} < B_{remnant} < 10\ \text{Gauss}$$

$$B_{inj} \cong 200 - 400\ \text{Gauss}$$

It is significant at the injection energy.

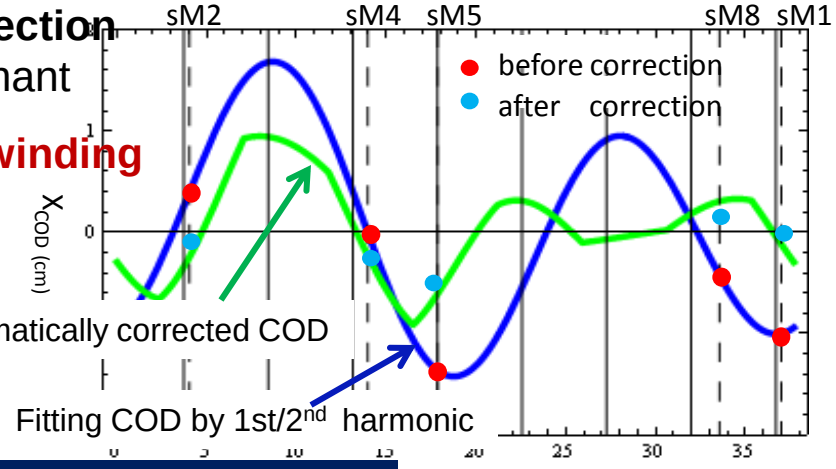
COD correction method:

limited number of position monitor (5) and no space for correction mag.

- 1st and 2nd **harmonic correction**
  Q_x =2.17 → N=1, 2 dominant
- **8 figure correction coil winding**

Results:

- Practically its size is acceptable.
- Current correction is still not enough; 3rd harmonic seems to appear in residual COD.

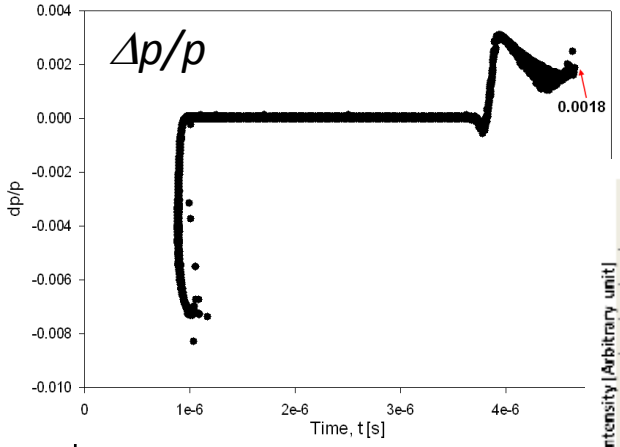


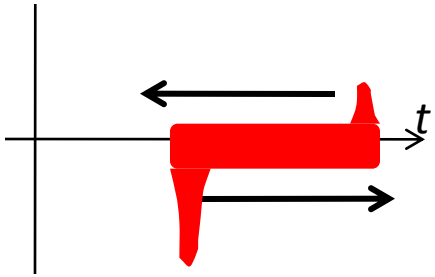
T.Yoshimoto, Poster

Beam Commissioning (1): Free Circulation at E_{inj} under B_{min}

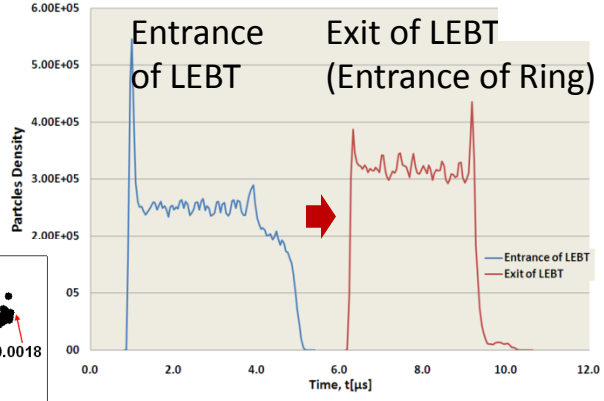
Notable facts in LEBT:

- Modulation in the momentum space caused by the transient fields of the chopper
- Drift compression

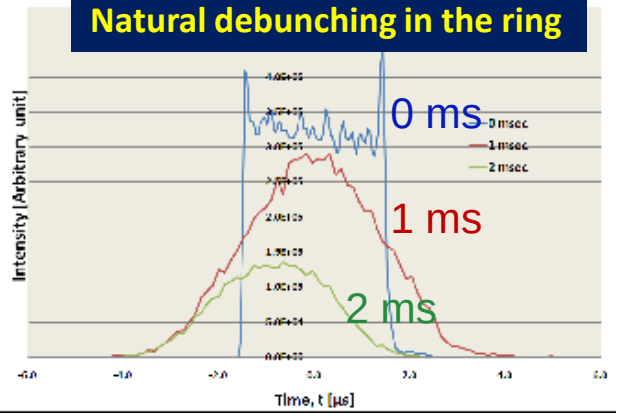




simulation



Natural debunching in the ring



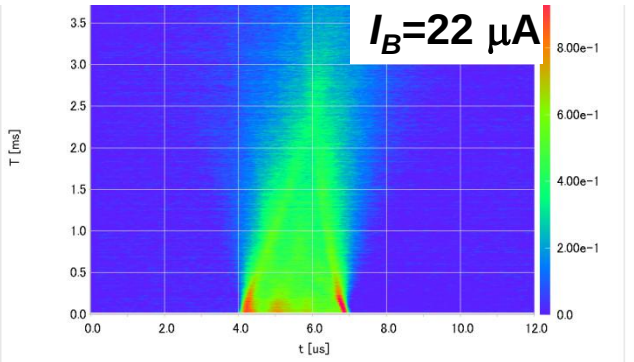
(~ 400 turns)

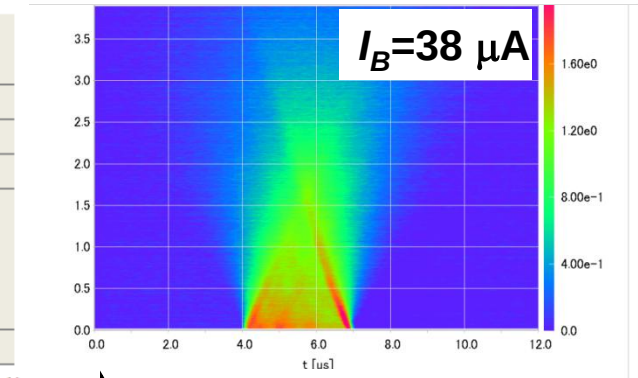
Slippage factor: $\eta = \frac{1}{\gamma_T^2} - \frac{1}{\gamma^2} \prec 0$

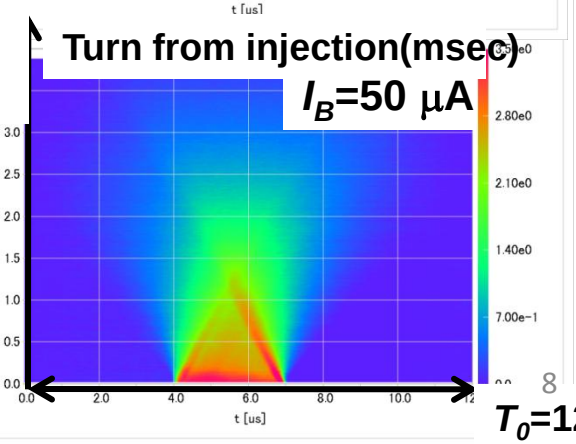
$$\Delta t \propto \eta \cdot \frac{\Delta p}{p}$$

2 msec

Projection of Bunch Signal Mountain view (3D) In Ring







T_0=12μsec

Notable facts in the ring:

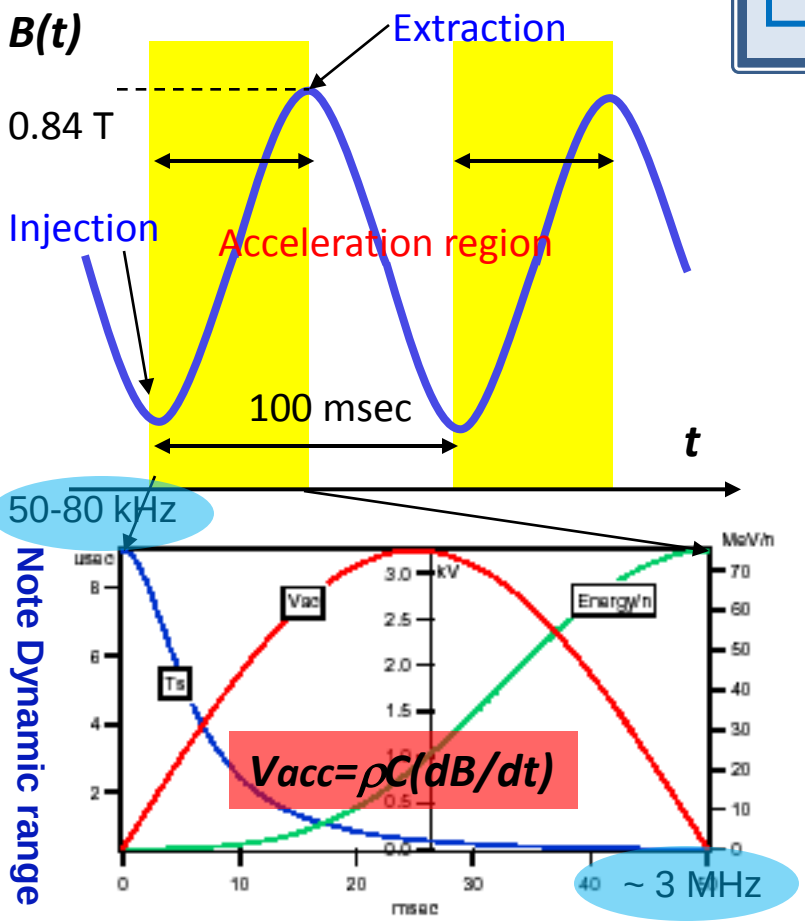
- Some spread in the momentum space
- Diffusion and further compression depends on beam intensity

K. W. Leo *et al.* "Einzel Lens Chopper and Behavior of the Chopped beam in the KEK Digital Accelerator", submitted to *Phys. Rev. ST-AB*

X. Liu *et al.*, "Longitudinal Beam Motion in the KEK Digital Accelerator", in *Proc. of HIAT2012* (2012).

Induction Acceleration Scenario in a Rapid Cycle Induction Synchrotron

Properties of Bending Fields in a Rapid Cycle Synchrotron



Technical Limitation of Induction Acceleration Cell

1) Fixed output voltage V_{out}= ~ 1 - 2 kV/cell

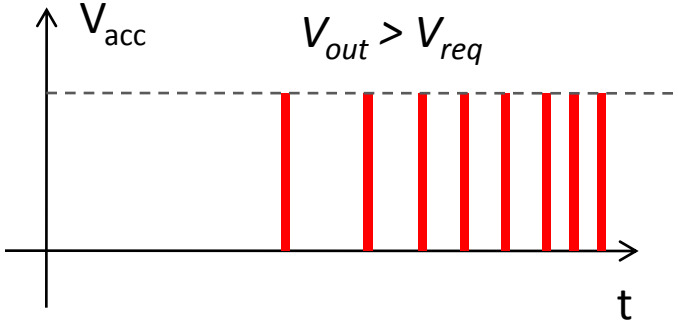
Primary voltage is not easily changed.

2) Maximum rep-rate ~ 1 MHz

Heat deposit is serious beyond 1 MHz.

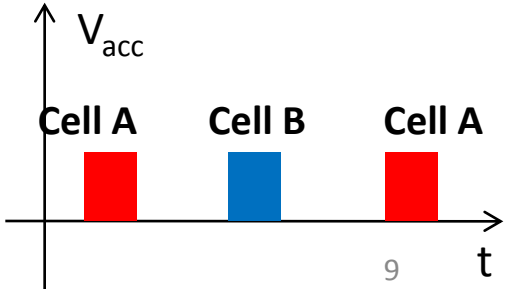
(If magnet ramping is slow)

1) Pulse density control



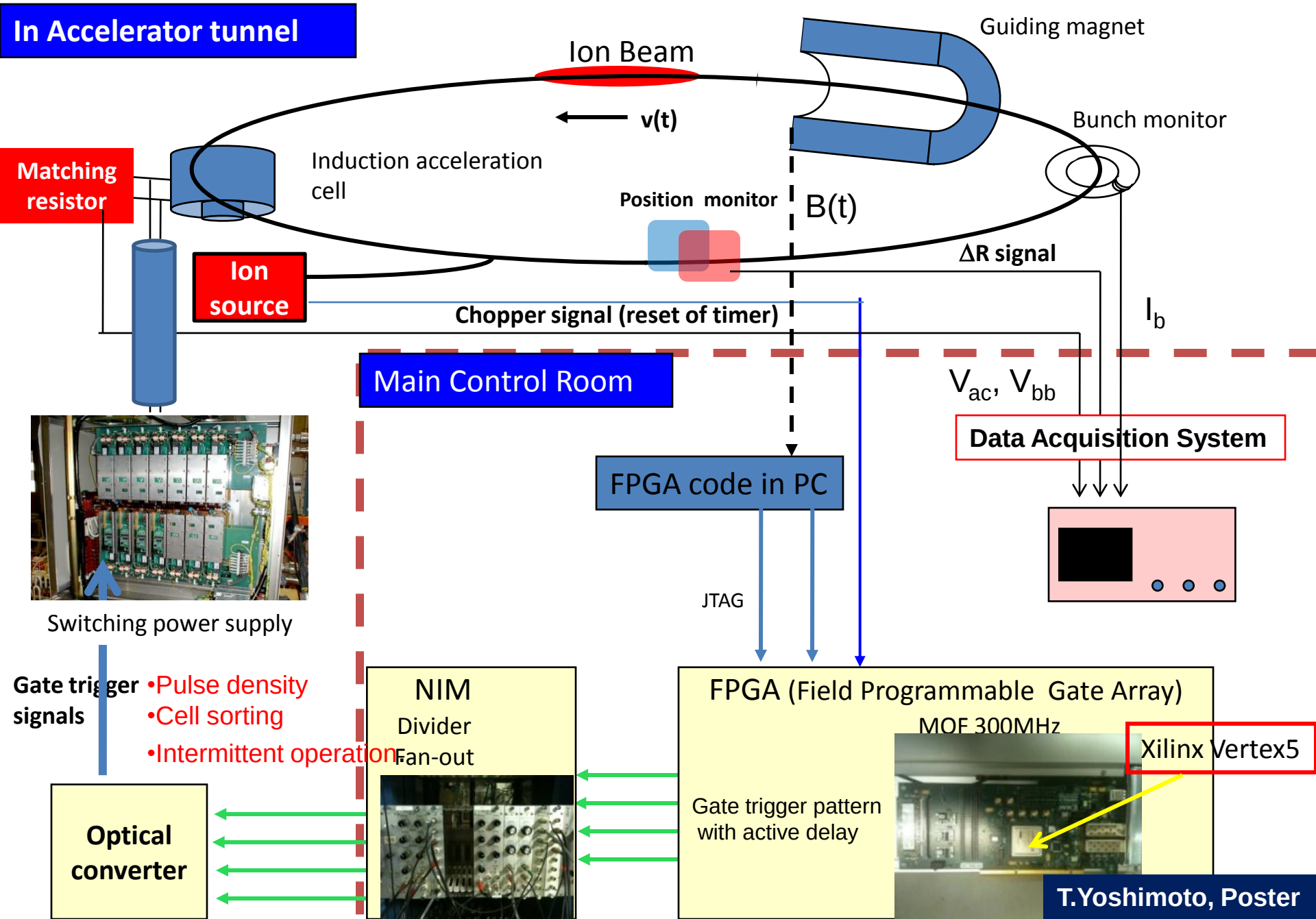
(If higher rep-rate is required)

2) Intermittent operation



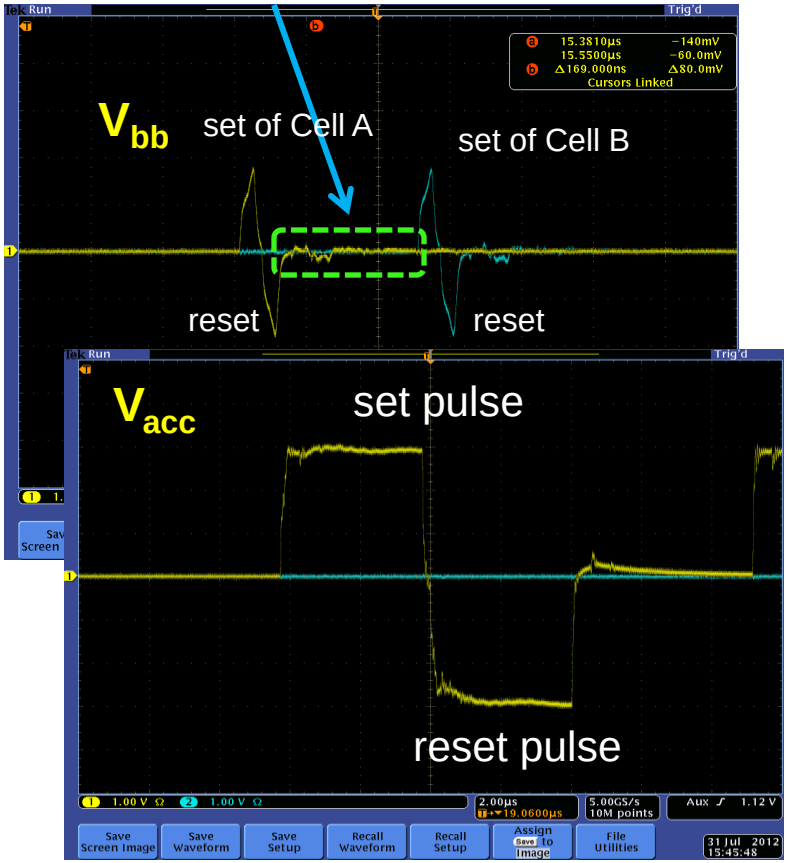
9

Fully Programmed Control System

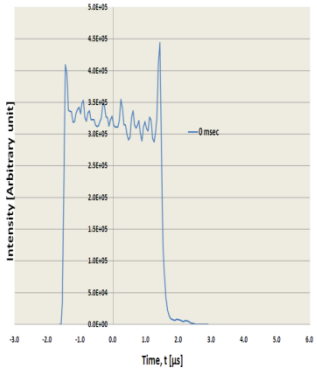


Confinement /Acceleration Voltage Pulses and Trapped Beam Pulse

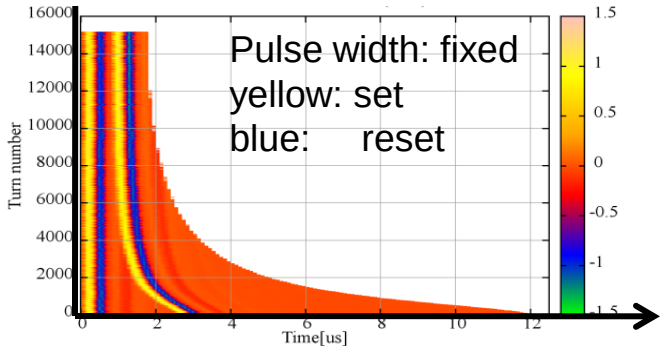
Trapping region *two Cells are employed*

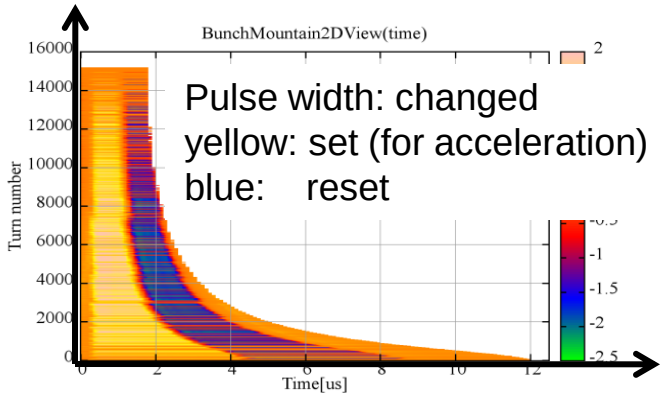


$I_B(t)$

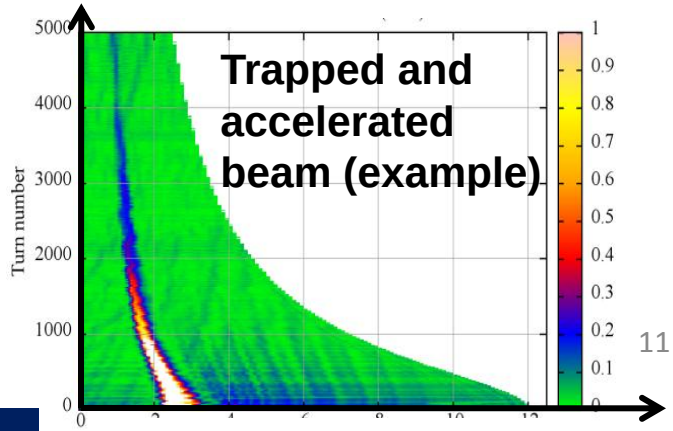


Projection of mountain views on the time-turn plane





Turn number

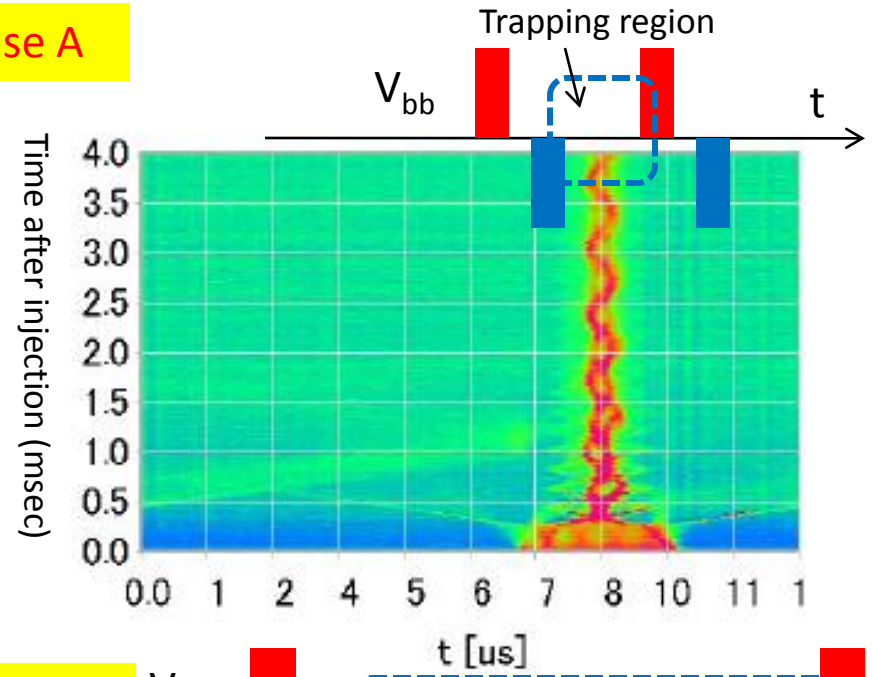


Revolution time frame

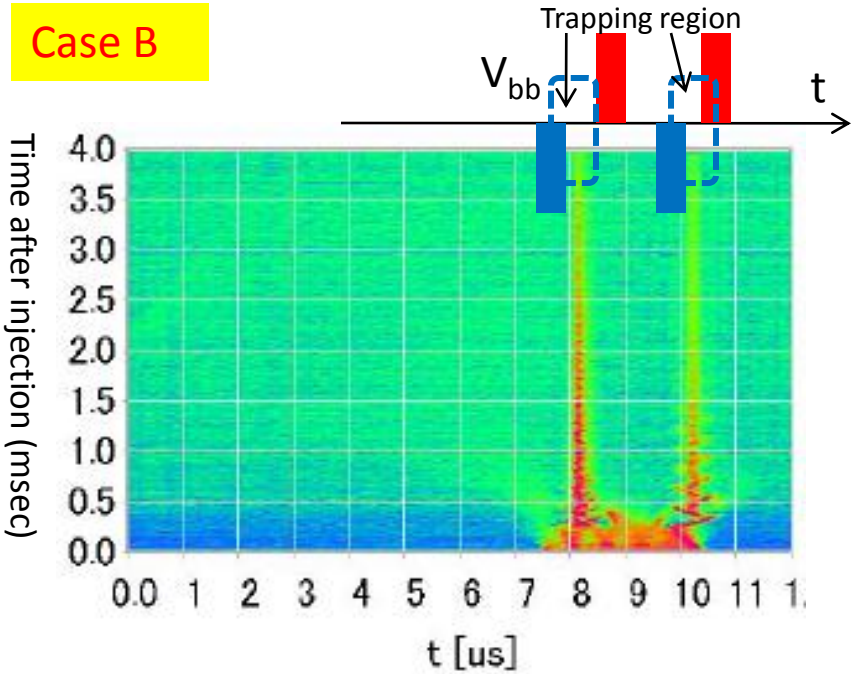
T.Yoshimoto, Poster

Beam Commissioning (2): Barrier Volt. Confinement at E_{inj} under B_{min}

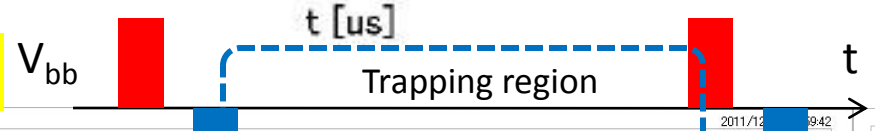
Case A



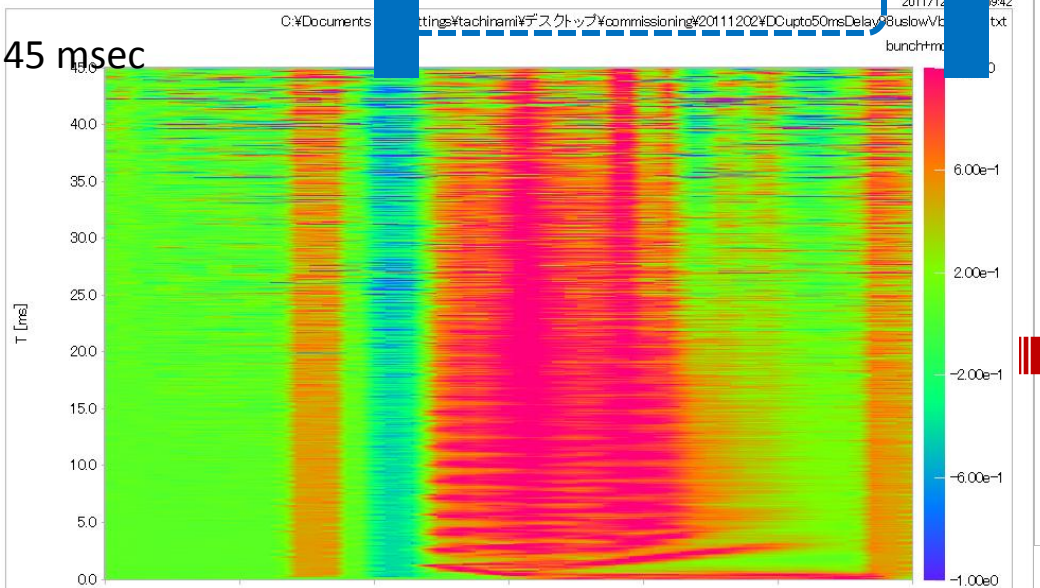
Case B



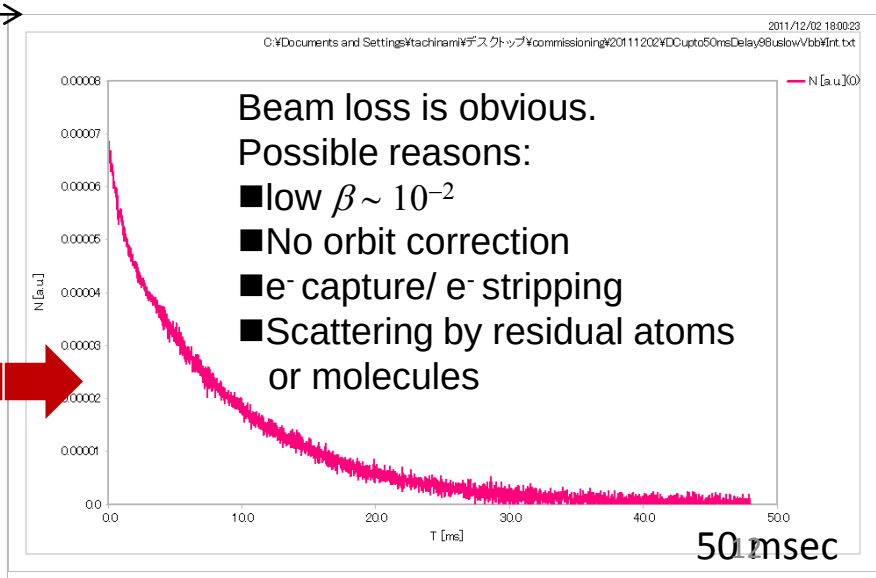
Case C



45 msec

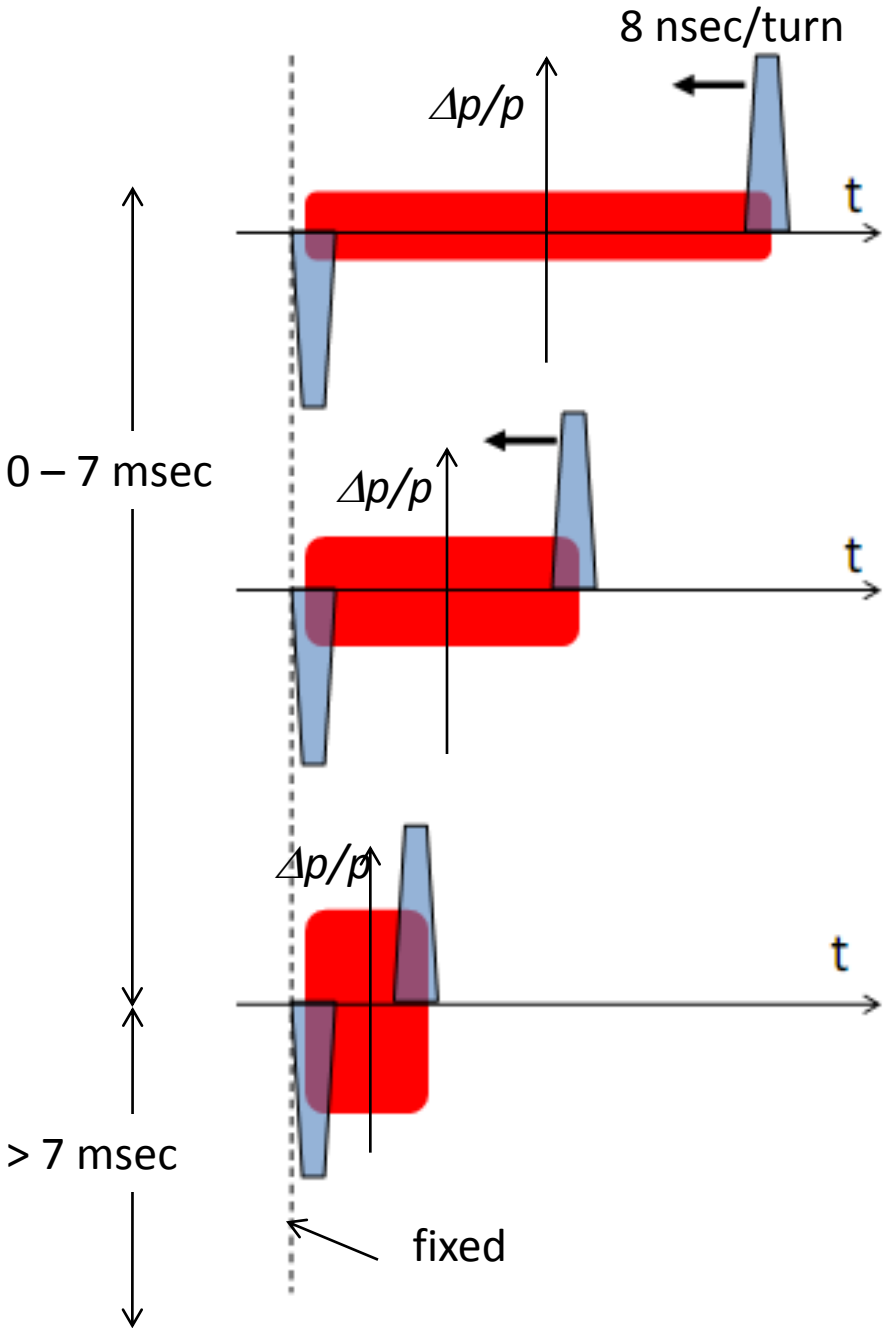


Beam survival



50 msec

Beam Commissioning (3): Bunch Squeezing Experiment

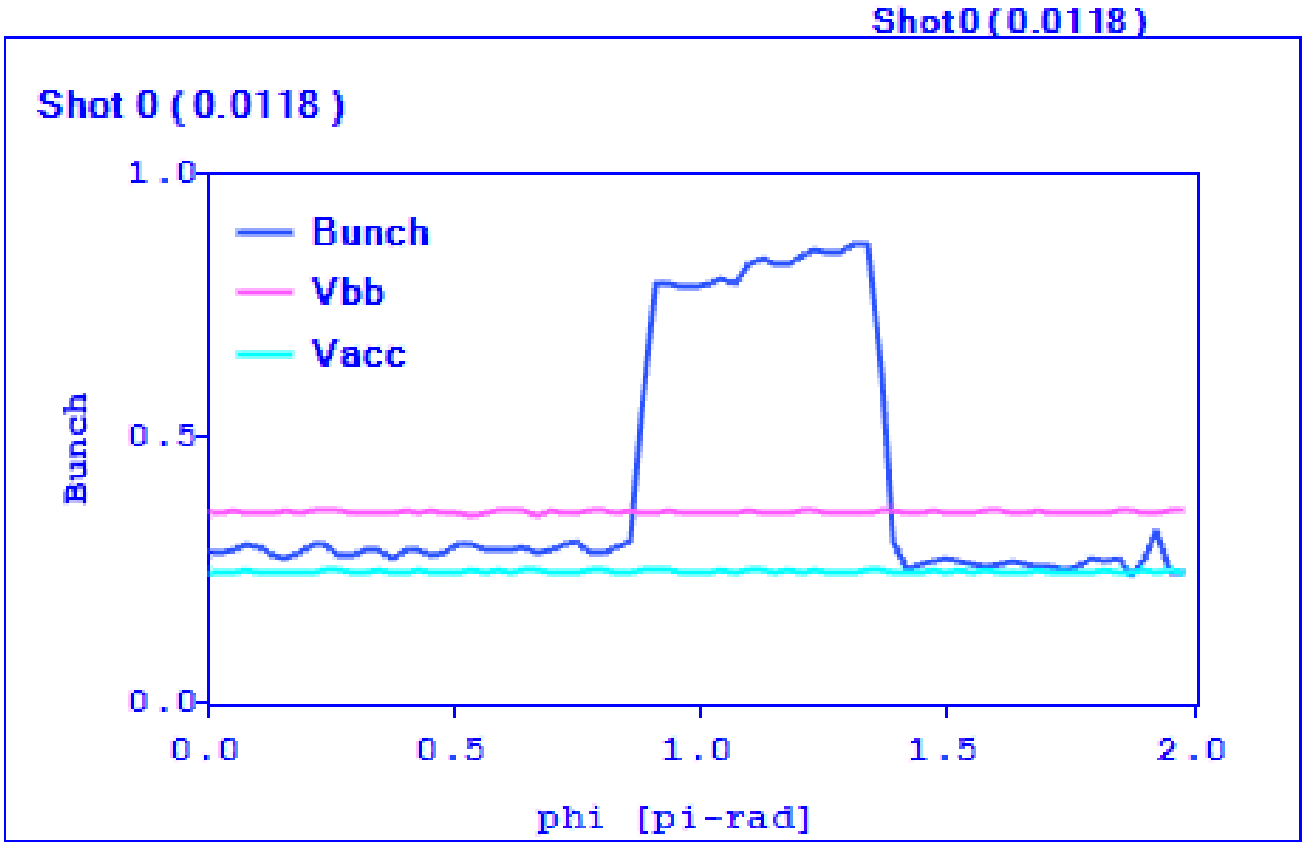


Bunch signal

Note: Polarity of barrier voltage signal is opposite.

Beam Commissioning (4): Demonstration of He1+ Acceleration (Preliminary)

Turn No Time after injection



He ion bunch signal

Barrier voltage pulse

Acceleration voltage pulse

Provided ion species and parameters at KEK Digital Accelerator

Ion source	ion	energy	Particle number/sec
ECR Ion Source	H, He, C, N, O, Ne, Ar	< 140 MeV/au, 200MeV	$<10^{10}$
Laser Ablation Ion Source	Xe, Fe, Cu, Ag, Au	< 70 MeV/au	$< 10^{9}$

Up-grade and coming fall Plans

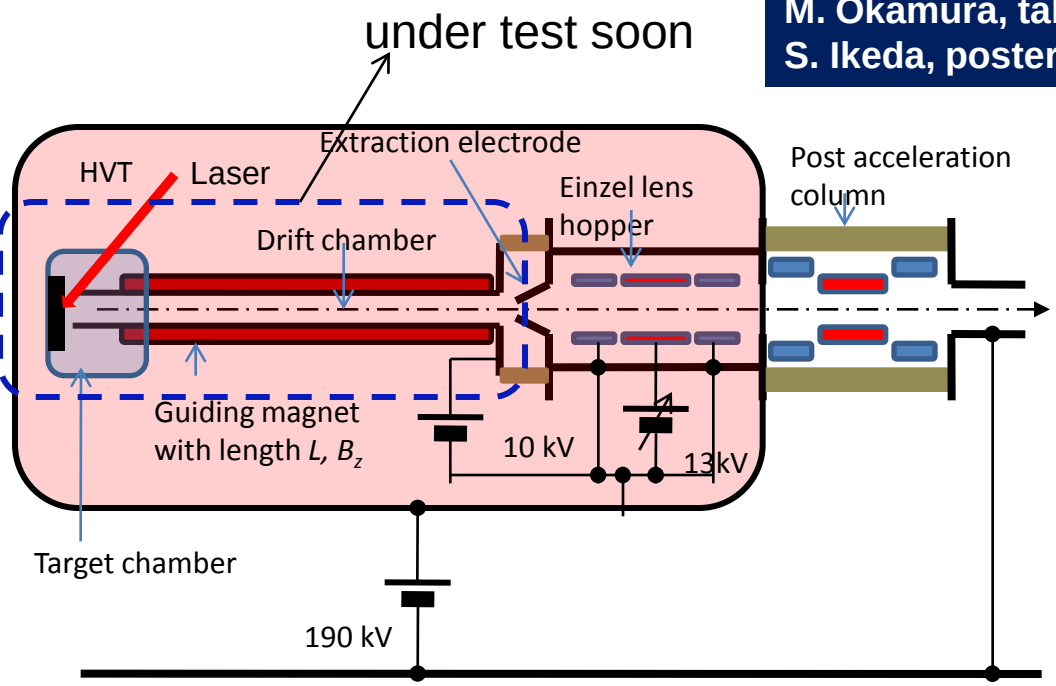
Increasing energy

Induction acceleration to the final energy (0.84 T)

1. by fully programmed control based on B-clock trigger
2. by Beam feedback control

Introduction of LAIS for Metal ions (Fe, Cu, Ag, Au))

M. Okamura, talk
S. Ikeda, poster



In collaboration with RIKEN-BNL Research Center/TokyoTech

Deliver of p, He, C, N, Ar to applications

(1) Laboratory Space Science
experiment using virtual cosmic rays
In collaboration with
JAXA-ISAS/NAO/Yokohama Nat. Univ.

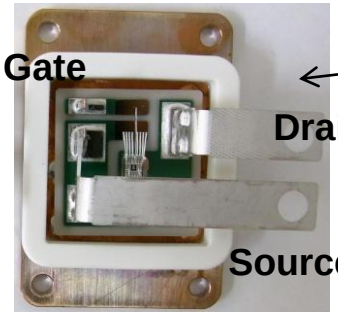
Next Generation of SPS and Test driving the Induction Cell at 1 MHz

From MOSFET to SiC-JFET

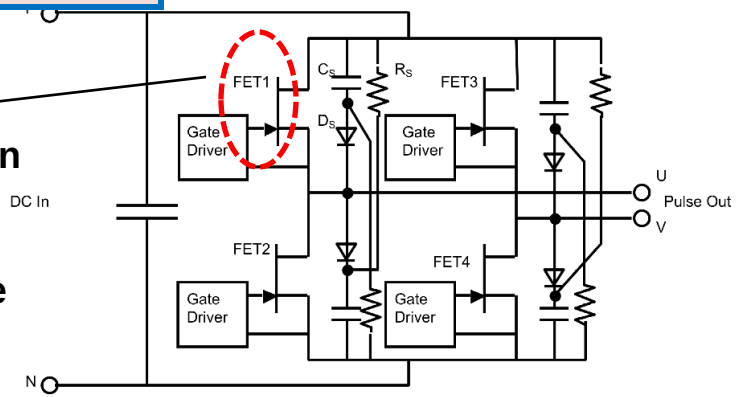
Properties of SiC:

- Wide band-gap
- Withstand voltage, 10 times higher
- Drift velocity of e^-, 2 times faster
- Thermal conductivity, 3 times better
- Operating temperature >300 ° C

1.2 kV, 50 A SiC-JFET (SICED)
Package devloped
by KEK/SunA

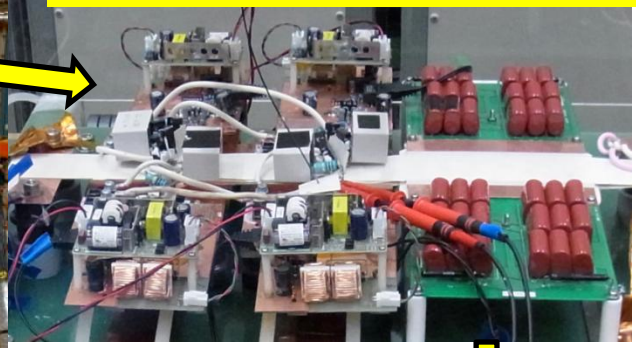


Circuit of the SPS

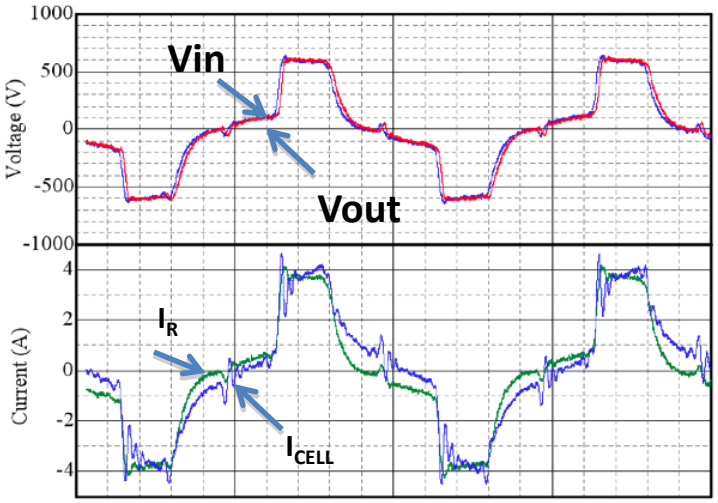


Present SPS (1st)
using 4x7=28 MOSFETs

Newly developed SPS (2nd)
using 4 SiC-JFETs
(still breadboard circuit)



Output Waveform in the Actual Cell Combination Test (100ns/div.) 1MHz



3rd generation

using 8 SiC-JFETs (2.4 kV, 50A) capability of removing heat deposit of 1kW, under development

by courtesy of K.Okamura (KEK)

Summary

- **Beam Commissioning of KEK Digital Accelerator integrating newly developed Einzel lens longitudinal chopper**
  - **Induction acceleration was confirmed (but not its final energy yet).**
  - **Beam handling using barrier voltage pulses was demonstrated with increasing freedom of beam handling in the longitudinal direction.**

Consequently,

- **it turned out that Induction Synchrotron Concept can work as**
  Slow Cycle Synchrotron (2 sec, KEK 12 GeV PS, 2006)
  Rapid Cycle Synchrotron (50 msec, KEK-DA, 2011)

- **New switching power supply based on SiC-JFETs for future high current IS has been demonstrated.**

- **Plan/possibility of applications utilizing heavy ions (virtual cosmic-rays) from DA**
  - ***Laboratory Space Science:*** **Systematic development of electric circuits to work in space (single ion phenomena), confirmation of "*origin of life*" (authorized)**
  - ***Industrial /medical use:***

Use of high energy ion track through materials

The next generation of hadron cancer therapy with option of *C-11 cancer therapy*

- ***Various beam handling experiment for HIF and WDM Science***